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Experimental investigation on double-impulse phenomenon of hybrid ceramic ball bearing with outer race spall

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ABSTRACT

Spall is a major fault type in rolling element bearings, which can produce specific vibration signals viz. double impulses. Previous reports indicated that the double impulses consist of two parts, the step response and the impulse response, which can be observed in the vibration generated by a spalled ball bearing. A step and an impulse responses will occur when a rolling element is entering and exiting the spall zone, respectively. Precise measurement of the space between the two parts can be employed to estimate the length of the spall zone along the rotating direction, and provide a possibility to evaluate the remaining useful life (RUL) of faulty bearings under running conditions. However, all the previous works are only concerned with the metal ball bearings. The double-impulse phenomenon generated by faulty hybrid ceramic ball bearings is rarely reported. To address this issue, the double-impulse phenomenon of hybrid ceramic ball bearings with different spall lengths on their outer races will be investigated in this paper. The prewhitening, kurtogram and squared envelop are employed to extract the two events (the entry and the exit) from the picked vibration. Experimental results indicate that the hybrid ceramic ball bearing with an outer race spall can generate shaper double-impulse phenomenon than that from the faulty metal bearings with almost the same outer race spall length.

1. Introduction

Rolling element bearings (REBs) are widely used in rotating machinery and their failures can lead catastrophic events. Thus the fault detection of REBs plays an important role in the fault diagnosis of rotating machinery. As well known, spall is one of the three main fatigue-fault types of bearings (surface distress, pitting and spalling), which usually leaves cavities on contact surfaces with a depth of 20–100 μm [1,2]. Generally, REBs can still work for a period of time when a tiny spall occurred [1]. A premature replace of faulty bearings can lead to increased cost. Hence, the evaluation of the remaining useful life (RUL) for faulty bearings is important. Previous work [1,3] presented that double impulses can be observed when a rolling element passing through a spall zone, and the size of the spall along raceway can be estimated by measuring the space between two consecutive impulses [1], which can provide a powerful way for evaluation of the RUL. The double

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impulses generated by the spalled metal ball bearing consist of two parts. One is defined as the step response generated by the entering event, and the other is the impulse response excited by the exiting event [1]. The two parts have different characteristics, the step response mainly contains low-frequency components, while the impulse response has a wide-frequency band. Some signal processing methods have been also proposed to extract the two events [3–5]. Among these methods, the so-called joint scheme has been proposed to process the two events together with the same parameters [1]. However, due to different characteristics of the two events, the joint scheme can not enhance and extract the two parts equally. Then a separation scheme has been introduced in [1], and used to extract the two parts at different frequency bands. Thus, the double impulses can be enhanced more prominent than that obtained by the joint scheme via the separation scheme. With this respect, an improved separation scheme will also be adopted in our research, which will be introduced in the following section.

Different to metal bearings, the rolling elements of hybrid ceramic bearings [6] are made of ceramic materials (Si_3N_4, etc.) instead of metal. However, this difference endows hybrid ceramic bearings with some unique characteristics such as low density, high hardness, and high-temperature resistant etc., which make hybrid ceramic bearings especially suitable for high-speed spindles of machine tools. On the other hand, the condition monitoring of hybrid ceramic bearings is also becoming essential for system operations. It is worth mentioning that spalling is also the main type of contact fatigue failures for hybrid ceramic rolling element bearings [7,8]. However, it has not been reported in the literature that whether the double impulses can be excited when the ceramic balls pass the spall zone on the outer race or the inner race. Then, the investigation of the double-impulse phenomenon of hybrid ceramic ball bearings is important. It will determine whether the evaluation of the spall length by the double-impulse measurement is also suitable to the hybrid ceramic ball bearings. Motivated by these facts, this paper aims to take an experimental investigation on the double-impulse phenomenon of hybrid ceramic ball bearings with spalled outer races. An improved separation scheme will be utilized to process the vibration, in which the spall related vibration is pre-whitened and separated into two parts (the entry event and the exit event) at first. Subsequently, the fast kurtogram algorithm [9] is utilized to enhance the two events by extracting the squared envelopes respectively. Lastly, the enhanced two events are added back together and normalized to indicate the double-impulse phenomenon clearly, which is used for accurate space measurement. The experiments based on a test rig confirmed that the double-impulse phenomenon generated by the faulty hybrid ceramic ball bearing with a spalled outer race can be observed. The vibration signals from the same-size spalled outer race hybrid ceramic ball bearings can induce a more prominent double-impulse phenomenon than that from the metal REBs.

This paper is organized as follows. In Section 2, the separation scheme and signal enhancement methods are introduced. Experiments and the corresponding analysis of the double-impulse phenomenon generated by hybrid ceramic ball bearings with spalls on the outer races are presented in Section 3. The relationship between the spall length and the space of double impulses, the shaft speed and the space of double impulses are discussed in Section 4. Conclusions are drawn in Section 5.

2. Separation scheme and signal enhancement methods

As mentioned above, the characteristics of the step and impulse responses in the double-impulse phenomenon are different. The joint scheme introduced in [1] can not be utilized to enhance the two events equally. For this reason, the separation scheme has been recommended in [1] to extract and enhance the two parts for the measurement. The separation scheme allows different parameters to be utilized to process the two events, and thus it is also adopted in this paper. The spall related vibrations are separated into two parts, viz. the step response train and the impulse response train at first. Correspondingly, the enhancement and the extraction methods are utilized to process the two events. As a result, the separation scheme can obtain both the enhanced step response train and the impulse response train. The previous schematic introduced in [1] and the improved version presented in this paper are shown in Fig. 1 (a) and (b) respectively. The main steps of the improved separation scheme are listed as follows.

Firstly, the autoregressive (AR) model based pre-whitening method is used to enhance the impulsiveness of the spall related bearing vibrations. The pre-whiten step can be expressed as in [10,11] by

$$\mathbf{e}_t = \mathbf{x}_t - \sum_{j=1}^{p} a_j \mathbf{x}_{t-j}, \tag{1}$$

where $\mathbf{e}_t$ represents the pre-whitened vibration (vector) , which mainly contains the interesting bearing fault related impulsive components and additive random noise, $\mathbf{x}_t$ and $\mathbf{x}_{t-j}$ are the vibrations at the time t and $t-j$, respectively, p denotes the AR order, and a_j represents the jth autoregressive weighted regression parameters.

To perform the separation of the two parts, the key is to locate references as start points of the separation. In this investigation, the time positions of the maximum amplitude of observed impulses are tracked firstly. Then these positions should be shifted to the forward about L sampling points to ensure references are located between the step and impulse responses. In this paper, L is determined by

$$L = \frac{f_s}{f_o} \times \frac{2\delta}{D}, \tag{2}$$

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